Estudio experimental del empuje sobre estructuras de contención en suelos reforzados con geomallas

Experimental study of the lateral earth pressure on retaining structures in soils reinforced with geogrids

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Resumen

Este artículo presenta un estudio experimental de la variación de las tensiones de empuje sobre una pared que soporta un suelo reforzado con geomallas. Para ello se utilizó un equipo diseñado y construido especialmente para ejecutar ensayos de empuje bajo condiciones de deformación plana. Se describe el equipo de ensayo y los instrumentos de medición, así como el suelo y la preparación de las muestras de arena y la geomalla utilizada. En la primera etapa de la investigación se ensayan muestras sin reforzar y se comparan los resultados con aquellos provenientes de las teorías clásicas de empuje. Posteriormente se presentan los resultados de ensayos de empuje en suelo reforzado con una, dos, tres y cuatro geomallas. Se concluye que la incorporación de geomallas como refuerzo en el suelo disminuye el empuje ejercido por el suelo sobre la estructura de contención. Esta disminución del empuje es de aproximadamente un 25% cuando se usa una geomalla, un 50% con dos o tres geomallas y de un 75% con cuatro geomallas para los espaciamientos, sobrecargas e incremento de desplazamientos usados. Resultó posible identificar que la distribución de la tensión de empuje con la profundidad no sólo no sigue la variación triangular sino que se desarrollan arcos de tensiones en el suelo entre las geomallas.

Palabras Clave: Deformación plana, empuje activo, empuje en reposo, geomallas, arcos de tensión

Abstract

This article presents an experimental study on the variation with depth of the stresses due to lateral earth pressure on a wall retaining a soil reinforced with geogrids. To this end, an apparatus was designed and constructed especially tailored for performing lateral earth pressure tests under plain strain conditions. The experimental apparatus and the measurement instruments as well as the soil and the sample preparation and the geogrids used, are described. In a first stage of research, samples without reinforcing are tested and the results are compared with those from classic earth pressure theories. Subsequently, results from lateral earth pressure tests in soils reinforced with one, two, three and four geogrids are presented. It is concluded that the inclusion of geogrids as soil reinforcement reduces the earth pressure on the retaining structure. This lateral earth pressure reduction is approximately of 25% when one geogrid is used, 50% with two or three geogrids and 75% with four geogrids for the spacing, surcharges and displacement increments used. It was possible to identify that the lateral earth pressure distribution with depth not only does not follow a triangular variation, but it develops stress arching in the soil and between the geogrids.

Keywords: Plain strain, active earth pressure, at rest pressure, geogrids, and stress arching

1. Introducción

1. Introduction

Nowadays the wide use of geosynthetic materials is practically unavoidable in construction works, mainly in road and drain works, among many other applications (Jones 1996; Müller-Rochholz 2008).

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Among these geosynthetic materials, the use of geogrids as a reinforcement element on retaining structures has increasingly been used for the replacement of traditional walls, for example any type of reinforced concrete wall (gravitational or cantilever). The selection of geogrids reinforcement is justified not only as the fastest constructive and better finishing choice, but most relevant because it offers better static and seismic responses. Severe damages have been observed in the access embankments and abutments of bridges located within the area affected by the earthquake of moment magnitude 8.8 in February 27th 2010 hitting Chile, from Valparaíso to Arauco (Verdugo et al., 2010; Hube et al., 2010). However, major damages have practically not been reported in geogrids reinforced road embankments, abutments and walls; the few cases known so far presented completely minor distresses likely to be restored. Las Ballenas bridges in the Penco-Talcahuano Interportuaria motorway; Bonilla roundabout in Concepcion; north entrance to Chiguayante and Temuco; rail road crossway in San Francisco de Mostazal and Costanera Norte in Santiago are examples of a better performance during the strong earthquake in February 27th 2010. Tatsuoka et al. (1998) reported that during Kobe earthquake in 1995, retaining structures in railroads embankments reinforced with geogrids were later employed and they received minor repairing works. That was not the case for traditional retaining structures (gravitational walls, cantilever walls and reinforced battered walls), which required significant repairing works due to severe damages.

In order to design retaining structures reinforced with geogrids, traditional theories of lateral earth pressures are generally used by assuming a uniform stress distribution on the retaining walls (Jones 1996; EBGeo 2009). In the case of surcharges, for example a footing resting on the wall upper zone; it is considered that lateral earth pressure is constantly distributed with depth. And in the case of lateral earth pressure behind the wall, it is assumed that it exerts a linear horizontal stress varying with depth, in accordance with Rankine or Coulomb theories; both developed during XIX and XVIII centuries, respectively. The study of a static case is a relevant issue, since the seismic earth pressure can be derived from a pseudo-static case, as occurring in the well known seismic earth pressure theory by Mononobe and Okabe.

Pachomow et al. (2007) present a database with their own data and with data from other authors, where experimental results (laboratory and in situ) as well as numerical results are shown. However, it is not clear or systematic to note the effect of overburden and wall displacement variations, neither the spacing effect between geogrids.

Therefore, this article studies such effects, not thoroughly explained yet, with the purpose of determining the lateral earth pressure variation over the retaining wall height. The wall is retaining a granular soil, initially without geogrids and subsequently employing geogrids as soil reinforcement. The employed physical model corresponds to a sandy soil sample vertically loaded and exposed to lateral displacement by means of a sophisticated test apparatus. Obtained results are compared, when possible with uniform distributions proposed by the classical theories of active or at rest earth pressures.

Test Equipment

The test apparatus designed and built by Ruiken et al. (2010 a,b) at the University of RWTH Aachen, is a steel structure anchored to a foundation slab as depicted in Figure 1. The central zone allows the elaboration of a sample of 1 m long per 1 m high and 0.45 wide. Such soil sample is able to exert lateral earth pressure independently on two mobile side walls (block movement indicated by arrows in Figure 2a). The sample may also be loaded on its upper zone, where a constant surcharge can be placed by means of a compressed air cushion. The sample front facing shown in Figure 1 and 2a are made of a thick glass and the opposite one located behind is made of steel; both facings are fixed, thus their motion is restricted. In this way, it is possible to reproduce plain strain conditions, which enable the simulation of retaining structures of a great length extent. The glass facing is made of a crystal plate of 106 mm thickness and has an ultimate deformation of 0.1 mm under 50 kPa surcharge loads (Hamm, 2008). The equipment walls deformations will be analyzed further on. Retractable walls have a latex surface which reaches an angle of friction of soil-latex interface of approximately 2.6° by using silicone grease of average viscosity. For the case of crystal wall friction angle of the interface glass-soil is about 7.5° .

Figura 1. Vista frontal del equipo de ensayo con muestra preparada con 4 geomallas
Figure 1. Front view of test apparatus including a sample prepared with 4 geogrids

Figura 2. Esquema del equipo experimental: a) vista frontal y b) vista superior
Figure 2. Experimental equipment sketch a) front view b) upper view

Data Acquisition

Table 1 summarizes the instruments employed to measure loads and deformations. Loads were measured by means of load cells type S. A pair of load cells installed in both mobile blocks, reacting inside the structural framework of test equipment, was employed to measure the resulting lateral earth pressure on each wall. It is worth mentioning that in order to develop the active earth pressure test, the mobile block supporting the wall with the soil behind was increasingly and manually displaced by means of a control lever (see arrows and control lever in Figure 2). In such a way it is possible to control and simulate the development of soil lateral earth pressure on the wall. Another pair of load cells was installed to measure the total strength taken by geogrids (Figure 5). Details concerning geogrids will be explained later on.

Normal horizontal earth pressure distributions over the retaining wall were determined by means of deformations measured by 20 strain gauges, each one installed at 50 mm depth (called loading cells in Figure 2). Strain gauges attached to the wall, measure the deformation as long as they are deformed and; by means of their own calibration they allow the calculation of the applied stress, that is to say horizontal earth pressure.

Tabla 1. Instrumentación digital de los ensayos

Table 1. Digital tests instrumentation

Instrumento Instrument	Fabricante y modelo Manufacturer and model	Rango de medición Measure Rank? Range	Montaje y función Assembling and functions
Celdas de carga Load cells	HBM-RSCM tensión y compresión HBM-RSCM tension and compression	0 a 20 kN 0 to 20 kN	Están instaladas entre los bloques móviles y el marco estructural de reacción, miden la fuerza sobre las paredes en contacto con el suelo Installed between mobile blocks and inside reaction structural block; measure the load on the walls in contact with the soil.
Celdas de carga Load cells	HBM-RSCM tensión y compresión HBM-RSCM tension and compression	0 a 20 kN 0 to 2 kN	Se encuentran fijadas en los sujetadores de la geomalla y por lo tanto miden la fuerza que toma la geomalla Attached to geogrid fasteners and therefore they measure stress exerted by geogrid.
Strain gauges	HBM 1-2441-6/120	0 hasta 2% de deformación 0 up to 2% deformation	Están colocados a lo largo de la pared cada 50 mm para determinar la distribución vertical de deformaciones horizontales y así el empuje Installed alongside the wall, every 50 mm, in order to determine vertical distribution of horizontal deformations and, therefore, soil pressure.

Fixed walls deformations

As previously indicated, the front glass facing of 106 mm has an ultimate deformation of 0.1mm under a surcharge of 50 kPa, according to Hamm (2008). From now on the distribution of horizontal earth deformation is shown, not only on the crystal facing, but also on the steel facing located at the opposite side. At different surcharge and undercharge levels, deformation was measured at several points by means of analog and electronic dials (Figure 3). Above was executed with the purpose of determining the influence of surcharge on the system deformation during a lateral earth pressure test, thus confirming the presence of plain strain conditions. From the measured results, it was determined that the glass facing deformations are higher than those in the steel facing. Furthermore, horizontal deformations of the glass facing, although reaching a value higher than 0.1 mm and, achieving an ultimate value of almost 0.25mm next to the base (dial 5) for a surcharge of 50 kPa, it is still restricted to no more than 0.24%. Therefore it is concluded that the testing equipment is adequate to study deformation conditions due to lateral earth pressure under plain strain conditions.

Figura 3. Disposición de los dials a) sobre la cara frontal de cristal y b) sobre la cara trasera de acero (dimensiones en mm)
Figure 3. Dials arrangement a) over crystal front facing and b) over back steel facing (dimensions in mm)

Mobile walls deformations

The horizontal deformation of side mobile walls, where lateral earth pressure takes place, is a subject of even most relevant to assess. For measuring purposes, dials placed at three points alongside the two mobile walls were used. Figure 4 shows the results of measurements of horizontal deformations during the tank filling and later under the application of different surcharge levels on the sample. It can be observed that from the application of a 20 kPa surcharge, horizontal deformations increase at great extent and an ultimate value is obtained for $\sigma = 50$ kPa. There is a difference in the horizontal deformation measured for the two walls. The first shows a deformation not exceeding 0.15 mm and the other reaches values of 0.8 mm. Such wall deformations should be taken into consideration for a further lateral earth pressure test, since they correspond to an initial condition of at rest pressure.

Figura 4. Deformación horizontal de las dos paredes móviles laterales durante el llenado y bajo sobrecarga
Figure 4. Horizontal deformations on two mobile side walls during filling process and under surcharge condition

2. Tested materials

Geogrids

Due to an agreement with the manufacturer, it is not possible to disclose the brand or the commercial name of geogrids. However, it is possible to indicate their main properties. According to the manufacturer the tested geogrid resists a tensile strength per linear meter, at least, of 30 kN/m. The relation between the tensile load and deformation of geogrids can be considered as linear from zero up to a tensile strength 15 kN/m, corresponding to a 5% deformation. As far as stiffness terms EA are concerned (Modulus of Young and Area A), derivative values obtained from limit strength of 2% reach a deformation of 600 kN/m; however, average values of 700 kN/m have been measured during tensile load tests of large width. The value measured directly from tensile tests of large width is considered more appropriate than that value provided by the manufacturer. The tested geogrid has white, plain and monolithical polypropylene straps, which are pre-stretched and welded at the nodes. Mesh woven size is 32.5mm x 32.5mm. Strap thickness is 0.9mm and junctions are 1.4mm.

Geogrids are connected at the mobile side ends to a bar specially designed to support each geogrids' strap, as indicated in Figure 5. This bar is connected to a load cell, which enables to measure the total or resulting load taken by the geogrids inside the soil.

Figura 5. Barra que sujeta las tiras de la geomalla conectada a una celda de carga, strain gauges en la geomalla
Figure 5. Bar supporting the geogrids straps connected to a load cell, strain gauges in the geogrids

On the other side, geogrids were implemented with strain gauges to measure deformations (Figure 5). Figure 6 presents an upper side view of geogrids showing the central layout for such deformation sensors, and others installed in an area next to the edge.

Figura 6. Posición de los strain gauges en la geomalla superior para el caso de ensayo con dos geomallas (geomalla inferior sin strain gauges)

Figure 6. Strain gauges arrangement in the upper geogrid, for the case of two-geogrids test (lower geogrids without strain gauges)

Granular soil

The soil under study is a sandy material extracted from Marienberg town in Germany. The sand has a grading distribution ranging from sieves DIN N°5 to N°230 (4 mm to 0.063 mm)

By means of drained triaxial tests, it was concluded that this sand has a maximum angle of internal frictional angle of 40° and cohesion of 0 kPa for lateral earth pressure conditions summarized in Table 2.

Tabla 2. Propiedades geotécnicas de la arena de Marienberg

Table 2. Geotechnical Properties of Marienberg's sand

Propiedad/Property	Valor/Value
Peso específico/Specific weight G_s	2.65
Índice de vacíos máximo/Maximum void ratio e_{max}	0.842
Índice de vacíos mínimo/Minimum void ratio e_{min}	0.482
Porosidad máxima/Maximum Porosity n_{max} %	45.70
Porosidad mínima/Minimum porosity n_{min} %	32.50
Peso unitario seco/Unit dry weight γ_d , kN/m ³	17.24
Porosidad/Porosity n , %	33.6
Índice de vacíos/Void ratio e	0.506
Densidad relativa/Relative Density RD , %	93.3

The sand samples were prepared by using a pluviation technique. The sand is placed inside a funnel and it descends by gravity throughout a tube of 1.5 m long and 45 mm internal diameter. It is possible to reduce the tube diameter by means of several plates with smaller diameters; the one used for the elaboration of twelve samples was of 13 mm. Above with the purpose of reducing once again the section where sand grains descend, thus increasing grains fall energy (Vaid and Negussey 1984). At the tube outlet, sand grains face a mobile conic device and they are pluviated in a radial way. The cone diameter at the very outlet area is 17 mm width, which turns into an outlet ring of 14 mm (Figure 7). The whole pluviation system moves covering the whole sample area, thus maintaining a constant rate at the grains falling section and also at the drop height, from the conical pluviation outlet up to the surface of the sample.

The maximum dry unit weights were of 17.2 kN/m³ app. (Table 2). The preparation of an unreinforced sample, for a relative density of 93%, took almost 6 hours; and duration increased when more geogrids were included.

Figura 7. Dispositivo cónico móvil de control de riego de arena, esquema en c) no está a escala
Figure 7. Mobile conic device to control sand pluviation; sketch on c) is not drawn to full scale

Test schedules and procedures

In a first stage tests were conducted on unreinforced geogrids samples; subsequently a geogrid was implemented in the center; two, three and up to four geogrids were uniformly spaced with depth. Loading conditions considered the sequential application of surcharge increments without displacing mobile walls. Subsequently, displacement increments of mobile walls, ranging from 0.1 mm to 10 mm were applied, thus allowing the determination of active earth pressure and its variation with depth, for a constant surcharge of 50 kPa. For tests in soils reinforced with geogrids, the mobile walls were displaced until the resulting active earth pressure was balanced by the resulting load taken by the geogrids.

Results from tests without geogrids

Figure 8a presents the horizontal earth pressure distribution measured by means of the vertical layout including 20 strain gauges, placed in the center of a mobile wall, and spaced every 50 mm. Experimental data correspond to the horizontal earth pressure distribution for six surcharge states σ . The increase of lateral earth pressure under surcharge becomes clear. There is a major increase of lateral earth pressure in the upper wall side with a value higher at 75 mm depth. Besides, lines are included which correspond to theoretical distributions of at rest pressure σ_{h0} and active earth pressure σ_{ha} . The determination of those lines considers the expressions by Jaky and Rankine for at rest pressure k_0 and active earth pressure k_a coefficients, respectively; by using the internal friction angle of soil $\phi = 40^\circ$ and the soil unit weight $\gamma = 17.24 \text{ kN/m}^3$ for the calculation of σ_{h0} and σ_{ha} .

$$\sigma_{h0} = k_0 \gamma z + k \sigma$$

$$\text{where } k_0 = 1 - \sin \phi \quad (1)$$

$$\sigma_{ha} = k_a \gamma z + k \sigma$$

$$\text{where } k_a = \frac{1 - \sin \phi}{1 + \sin \phi} \quad (2)$$

Triangular linear theoretical distributions with depth approximate to values measured from the central zone from 0.175 m and 0.825 m, without or with low surcharge. Furthermore, when experimental values tend to follow a linear distribution, the values are between the lines of at rest and active cases. In effect, for data in Figure 8a, the active case should not be valid since the wall was not displaced. However, the lateral earth pressures are reduced for at rest case and approximate to active case, since walls are deformed. This is caused by the at rest pressure and due to surcharge, as it was shown in Figure 4. As observed in Figure 9a small deformations (displacement $u_x = 0.2$ mm) are enough to develop active earth pressure. Going back to the case of only surcharge variation, without walls displacements, $u_x = 0$ is presented in Figure 8b, which corresponds to a distribution with lateral earth pressure coefficient K with depth, expressed as:

$$K = \frac{\sigma_h}{\sigma_v} = \frac{\sigma_h}{\gamma Z + \sigma} \quad (3)$$

Where σ_h is directly determined from tests. Once again theoretical values k_0 y k_a are only to be considered as the range where measurement determined values are contained for the central wall zones, since in the upper zone data move away from theoretical values, mainly because of surcharge effect. The lower zone presents a boundary effect because the wall base is in direct contact with the sand sample base. A simulation case is established for a very stiff foundation soil, for example rock or cemented soil. That is why load transference or horizontal earth pressure takes places towards the base as a vertical earth pressure effect. This is also known as stress arching effect. It was not possible to measure such vertical load transferred from the bottom soil to the equipment base.

Figura 8. Suelo sin refuerzo; variación con la profundidad de a) la tensión de empuje horizontal y b) del coeficiente de empuje lateral, para el caso con $u_x = 0$ y σ variable

Figure 8. Unreinforced soil; variation with depth a) horizontal earth pressure stress and b) lateral earth pressure coefficient, for the case of $u_x = 0$ and σ variable

The lateral earth pressure variation with depth for different displacement levels of mobile wall are presented in Figure 9a. The wall horizontal displacement required to develop the active earth pressure is proportional to the wall height and to the soil stiffness. According to Sowers (1979) the minimum displacement required for the case of dense granular soils is $0.0005H$, where H is wall height. Being $H = 1$ m, displacement $u_x = 0.5$ mm.

By observing both graphs in Figure 9, it is noticeable that active earth pressure is developed in the center zone for the case $u_x = 0.2$ mm. Such difference of 0.3 mm may be produced, as already mentioned, because the wall undergoes initial deformations due to at rest pressure and surcharge. For the cases with $u_x > 1$ mm, the active earth pressure theory is no longer valid because lateral earth pressure values are considerably reduced because of the relaxation or decrease of horizontal earth pressure stress.

Figura 9. Suelo sin refuerzo; variación con la profundidad a) de la tensión de empuje horizontal y b) del coeficiente de empuje lateral, para el caso de $\sigma = 50$ kPa/m y u_x variable

Figure 9. Unreinforced soil; variation with depth a) horizontal earth pressure stress and b) lateral earth pressure coefficient, for the case of $\sigma = 50$ kPa/m and u_x variable

Test Results with geogrids

Lateral earth pressure test results are now presented for the cases of one, two, three and four geogrids. The Figure 10a presents the lateral earth pressure exerted by a soil reinforced with two geogrids on the fixed wall, i.e., without applying wall displacement, but varying the surcharge from 0 to 50 kPa/m. The geogrids are placed at 0.3 m and 0.7 m depth, respectively. At rest pressure and active earth pressure theoretical curves have been included in the graph, the same as in the case of unreinforced soil case. It can be observed that for the case without surcharge, theoretical curves are able to approximately represent experimental data only up to 0.5 m, which is the most reduced section for the case of unreinforced soil presented in Figure 8a. From 0.5 to 1 m, theoretical earth pressures overestimate the measured lateral earth pressures. It means that geogrid is taking some portion of at rest pressure. Subsequently, when surcharge is applied the same effect takes place, i.e., the lateral earth pressure measured from the wall with reinforced soil is lower than the one measured from the wall with unreinforced soil.

Figure 10b presents the upper geogrid deformation, which is stretched due to the increase of lateral earth pressure due to surcharge. The geogrid is fixed only at one end while the other is free. Because of this difference of boundary conditions at their ends, deformation distribution is not symmetrical. Geogrid fixation by means of a cross bar connected to a load cell is presented in Figure 5 and the arrangement of strain gauges in the geogrid is presented in Figure 6. These strain gauges enable the measurement of deformation effect at the center and alongside the geogrids. It must be noted that geogrid is most deformed in the zone where it is fixed contrarily to the end where the geogrid is not fixed. A discharge of 50 to 0 kPa/m is included subsequently a recharge from 0 to 50 kPa/m is applied. Although unloading reduces deformation, the latter does not return to values close to zero. However, during reloading deformation does return to values close to that for 50 kPa previously applied. It means that during initial load, plastic deformations take place and, during unloading and reloading cycles, deformations are of elastic or recoverable type.

Figure 10. Suelo con dos geomallas de refuerzo; a) variación con la profundidad de la tensión de empuje horizontal y b) deformación de la geomalla superior en el plano horizontal para el caso de σ variable y $u_x = 0$

Figure 10. Soil reinforced with two geogrids a) variation with depth for horizontal earth pressure stress and b) upper geogrid deformation on a horizontal plane for the case of σ variable and $u_x = 0$

After completing the earth pressure tests due to surcharge, the wall was successively displaced in order to apply different states of active earth pressure. The results from active earth pressure under a constant surcharge of 50 kPa/m and incremental displacements on one wall are presented in Figure 11a. The active earth pressure line has been also superimposed here for comparison. The theoretical line is only valid for the first 0.2 m, for a displacement of 0.2 mm. For displacements higher than 1 mm, a considerable active earth pressure increase takes place in the upper zone.

However, the contrary occurs from 0.2 m and lower, since lateral earth pressure successively decreases with u_x , even reaching negative earth pressure values. Such negative values indicate that a passive earth pressure would be taking place because of geogrids tensile stress.

Figure 11b presents the results from upper geogrid deformation due to displacements sequences applied on the wall, causing active earth pressure. Those results are the continuation of deformations measured for the surcharge increase case. Once again it is observed that deformation increases in the zone where geogrid is fixed. This increase becomes quite considerable in the fixed end, however, quite slight in the free end, showing a irregular deformation variation between both ends.

A third loading state was analyzed by means of displacement applications on the other wall, located at the opposite side to the wall already tested. Figure 11c presents deformation results from the same geogrid, which are superimposed to previously measured deformations. At this time it is observed that geogrid at the free end is also deformed, although a deformation in the fixed end also takes place, accumulating a deformation value of 0.64%. This value is more than twice the deformation measured in the remaining 90% of the geogrid. The 0.64% value of deformation 64% corresponds to the load taken by the geogrid which is approximately 2 kN. By observing Figure 13, it is noticeable that this load practically corresponds to the half of the active earth pressure developed for a 2mm displacement, in the case of two geogrids.

Figura 11. Suelo con dos geomallas de refuerzo; a) variación con la profundidad de la tensión de empuje horizontal, b) y c) deformación de la geomalla superior en el plano horizontal para el caso $\sigma = 50$ kPa/m y u_x variable en ambas paredes
 Figure 11. Soil reinforced with two geogrids a) variation with depth for horizontal earth pressure stress b) and c) upper geogrid deformation on the horizontal plane for the case $\sigma = 50$ kPa/m and u_x variable in both walls

The series of tests concluded with the inclusion of three and four geogrids as reinforcement under the same initial surcharge conditions. Subsequently, displacements were applied to the wall with fixed geogrids and later on the wall with loose geogrids. The results on lateral earth pressure over walls with fixed and free geogrids are similar and, the cases with free geogrids are presented below.

Figure 12 presents the case of a soil reinforced with three geogrids applying successive displacements on the free geogrids wall. There is no evidence of similarity between the theoretical linear distribution of active earth pressure, which in fact acquires a contrary trend, i.e., lateral earth pressure decreases with wall height. There is a slight increase of lateral earth pressure under the geogrids, which is also noticeable in the case of two and four geogrids. Generally, it is possible to detect the presence of a stress arching between geogrids. It reflects the geogrids ability to absorb some or great lateral earth pressure portion, which is well evidenced in Figure 12b, with four geogrids. This stress arching effect transfers maximum stresses to the wall between geogrids and minimum stress just where the geogrids are. That is why the lateral earth pressure on the wall is reduced as long as the number of geogrids increases. Although this arching mechanism has already been observed by Pachomov et al. (2007) in laboratory tests with walls 3m height, it has not been so clear and systematically observed because of few instrumentation was available and greater reinforcement spacings.

To analyze the effect of geogrids quantity on the lateral earth pressure, expressed as the resulting lateral earth pressure strength as a function of the wall displacement, the graph presented in Figure 13 has been made. Such resultant loads of lateral earth pressure were measured by loading cells behind mobile walls. The resultant load values of lateral earth pressure measured by loading cells are well correlated with the resultant load of lateral earth pressure obtained from integration along the wall height for the measured curves σ_h . In Figure 13 it can be noticed that active earth pressure is reduced in approximately 25% when one geogrid is used, 50% with two geogrids and 75% with four geogrids. Similar results are obtained when two and three geogrids are used. This demonstrates that the use of geogrids, as soil reinforcement behind retaining structures, is a good choice to reduce lateral earth pressure.

In Figure 13 curves do not begin from a zero displacement, because as explained earlier, deformations are developed in mobile walls during the initial surcharge stage, which results in a difference for initial values. Since slight displacements take place (up to 0.3 mm) on the wall during surcharge stage, the geogrid is activated before displacement phase (Figure 4). That has a constructive implication to be considered in the design of retaining structures. In other words, controlled initial deformations and slight wall deformations should be allowed during construction to reduce or to avoid the initial at rest pressure.

Figura 12. Variación de la tensión de empuje horizontal con la altura para suelo reforzado con a) tres y b) cuatro geomallas para el caso de $\sigma = 50$ kPa/m y u_x variable

Figure 12. Variation of horizontal earth pressure stress versus height for a soil reinforced with a) three and b) four geogrids for the case of $\sigma = 50$ kPa/m and u_x variable

Figure 13. Variación de la fuerza de empuje versus el desplazamiento horizontal del muro para los casos sin y con varias geomallas de refuerzo

Figure 13. Lateral earth pressure strength variation versus wall horizontal displacement for cases with and without several reinforcement geogrids

3. Conclusions

This article has presented and analyzed a sophisticated experimental apparatus, which enables the study of lateral earth pressure under plain strain conditions. Results obtained from a series of tests on a smooth wall retaining soil with and without geogrid reinforcements, are initially interpreted according to at rest pressure and active earth pressure theories. It is shown that there is a clear decrease of horizontal earth pressure when geogrids are used. Furthermore, the use of geogrids favors the reduction of lateral earth pressure between geogrids. The mechanism that enables such decrease is associated to the development of stress arching. Such stress arching enables the reduction of lateral earth pressure where geogrids are located and increases lateral earth pressure between geogrids to a maximum value. The load taken by geogrids acts in opposite direction to that of the lateral earth pressure, thus partially absorbing soil horizontal stress against the wall. Distance between geogrids is a factor controlling the development of stress arching. The lower the distance between geogrids, the greater defined the formation of stress arching.

Deformation alongside the geogrid varies for each loading phase, as well as the and whit that the absorption or not of load, thus reaching a maximum next to the wall, which indicates the lateral earth pressure proportion taken by the geogrid.

Horizontal earth pressure is reduced in 25%, 50% and 75% depending on the use of one, two, three or four geogrids, respectively.

Furthermore it was observed that geogrid absorbs loads before beginning wall displacement, i.e. during surcharge application stage.

Further research is required to study the effect of less rigid soil foundation than filling soil behind the wall and, to study the effect on wall stiffness.

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